Student ID	3200110970	Pre-lab	/20
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Semester/Section		Total	/70

Lab 2: Op-amps

Labs 2 and 3 study operational amplifiers, or "op-amps." Op-amps were originally developed to implement mathematical operations in analog computers, hence their name. Today, op-amps are commonly used to build amplifiers, active filters, and buffers. You will work with many of these circuits in lab. The following table contrasts ideal versus practical characteristics of typical op-amps.

Op-Amp Property	Ideal	in practice
Gain A	∞	very large, $\sim 10^6$ and constrained by supply voltage
R_i	∞	very large, $\sim 10^6\,\Omega$
R_o	0	very small, $\sim 15\,\Omega$
Frequency response	flat	gain depends on frequency

The objective of this experiment is to gain experience in the design and construction of operational amplifier circuits. You also will examine some non ideal op-amp behavior.

By the end of Lab 2, you will have designed and built two amplifiers for your radio circuit. Once you have verified that they work, you will connect them to your envelope detector from Lab 1 and listen to synthetic AM signals.

1 Prelab

In the prelab exercises, you will review the analysis of op-amp circuits and design amplifiers for your radio circuit.

1. Assuming an ideal op-amp, derive an expression for the output voltage v_o in the circuit of Figure 1 in terms of v_1, v_2, and v_3. Hint: Notice that v_+ is equal to v_- , then write the KCL eq. for the node v_- and solve for v_o.

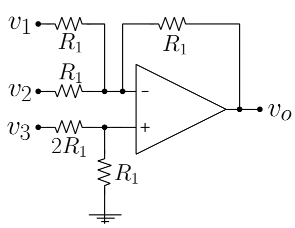


Figure 1: Op-amp circuit.

Show your work:

KCL
$$\begin{cases} V_+ \approx V_- \\ \dfrac{V_3 - V_+}{2R_1} + \dfrac{0 - V_+}{R_1} = 0 \Rightarrow \dfrac{V_3 - 3V_+}{2R_1} = 0 \Rightarrow V_3 = 3V_+ \\ \dfrac{V_1 - V_-}{R_1} + \dfrac{V_2 - V_-}{R_1} = \dfrac{V_- - V_0}{R_1} \Rightarrow \dfrac{-(V_1+V_2)+3V_-}{R_1} = \dfrac{V_0}{R_1} \end{cases}$$

$$V_0 = V_3 - V_1 - V_2$$

$v_o =$ $V_3 - V_1 - V_2$ (____/5)

2. Assuming an ideal op-amp, write two KCL equations in terms of v_x that relates the output voltage to the input voltage for the circuit in Figure 2 (you do not need to solve the KCL equations). Simplify your expressions as much as possible.

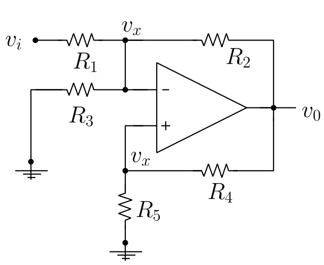


Figure 2: Op-amp circuit.

KCL1 : $\dfrac{V_i - V_x}{R_1} + \dfrac{0 - V_x}{R_3} = \dfrac{V_x - V_0}{R_2}$ (____/2)

KCL2 : $\dfrac{0 - V_x}{R_5} = \dfrac{V_x - V_0}{R_4}$ (____/2)

3. Again assuming an ideal op-amp, derive an expression for the output voltage v_o in the circuit in Figure 3.

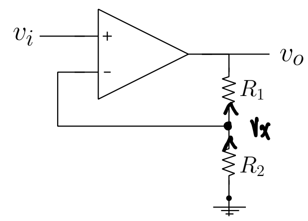


Figure 3: Op-amp circuit.

Show your work:

$$\begin{cases} \frac{0-V_x}{R_2} = \frac{V_x - V_o}{R_1} \\ V_x \approx V_i \end{cases} \Rightarrow V_i\left(\frac{1}{R_1}+\frac{1}{R_2}\right) = \frac{V_o}{R_1}$$

$$\therefore V_o = \left(1+\frac{R_1}{R_2}\right)V_i$$

$v_o =$ $\left(1+\frac{R_1}{R_2}\right)V_i$ (____/4)

(a) For a gain $\frac{v_o}{v_i}$ of 2, how must R_1 and R_2 be related? $R_1 = R_2$ (____/1)

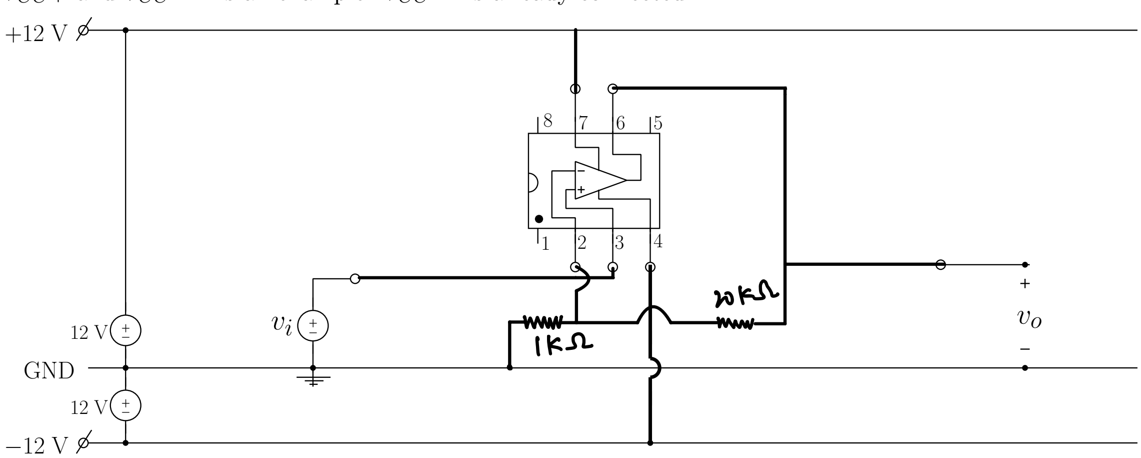
(b) For a gain $\frac{v_o}{v_i}$ of 21, how must R_1 and R_2 be related? $\frac{R_1}{R_2} = 20$ (____/1)

(c) How do you build two amplifiers, one with a gain of two and one with a gain of 21, given the following four resistors: one 1 kΩ, two 10 kΩ, and one 20 kΩ?

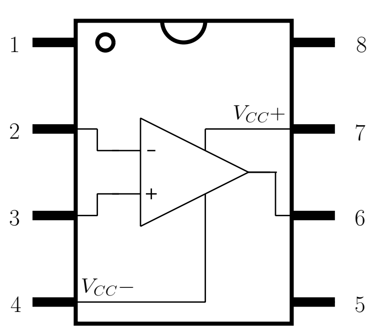
Gain of 2 : $R_1 =$ 10kΩ and $R_2 =$ 10kΩ	Gain of 21: $R_1 =$ 20 kΩ and $R_2 =$ 1 kΩ

(____/2)

(d) Using the pin-out diagram in Figure 4 as a reference, draw how you will wire the amplifier with a gain of 21. Draw in resistors and wires as needed. Include wires for input v_i, output v_0 and the bias voltages $V_{CC}+$ and $V_{CC}-$. As an example "$V_{CC}-$" is already connected.



(____/3)



Pins 1,5	offset null correction — not used
2	inverting input (-)
3	non-inverting input (+)
4	$V_{CC}-$ supply set to -12 V (DC)
7	$V_{CC}+$ supply set to 12 V (DC)
6	output voltage v_o
8	not connected

Figure 4: Pin-out diagram for the 741 op-amp.

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2 Laboratory exercise

- Equipment: Function generator, oscilloscope, protoboard, loudspeaker, audio jack, RG-58 cables, Y-cables, and wires.
- Components: two 741 op-amps, two 33 μF capacitors, one 1 kΩ resistor, three 10 kΩ resistors, one 20 kΩ resistor, and one 100 kΩ resistor, and a 0.1 μF capacitor (use the one from lab#1).

2.1 Using the 741 op-amp

The 741 op-amp contains a complex circuit, composed of 17 bipolar-junction transistors, 5 diodes, 11 resistors, and a capacitor that provides internal compensation to prevent oscillation. When wiring your circuits, however, you only have to make the usual connections: the inverting and non-inverting inputs, the output, and the positive and negative DC supplies. Figure 4 labels and describes the pins.

- The DC supplies must be set carefully to power the op-amp without destroying it:
- The DC sources should be set to +15 V for $V_{CC}+$ supply and -15 V for $V_{CC}-$ supply.
- The $V_{CC}+$ and $V_{CC}-$ supplies always stay at the same pins throughout the experiment. Do not switch them or you will destroy the op amp!
- When you are ready to turn the power on, always *turn on the DC supplies first*, then the AC supply.
- When you turn the circuit off, always *turn off (or disconnect) the AC first* and then the DC.

2.2 An op-amp amplifier

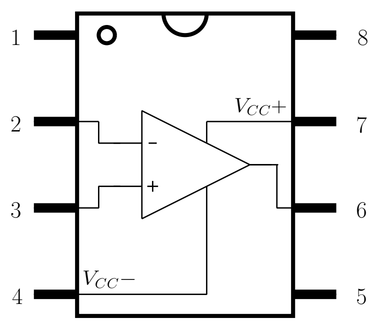


Figure 5: Pin-out diagram for the 741 op-amp.

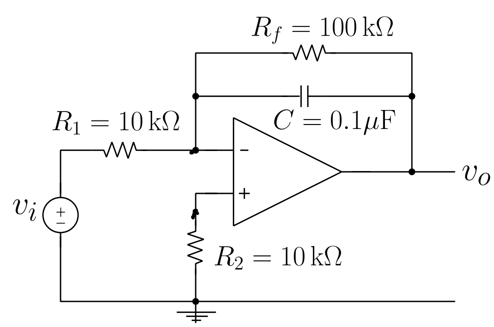


Figure 6: Integrating amplifier.

1. Configure the op-amp amplifier circuit shown in Figure 6 on your protoboard using component values of $R_1 = 10$ kΩ, $R_2 = 10$ kΩ, $R_f = 100$ kΩ, and $C = 0.1\,\mu$F (Use the one from lab#1). *In this and all future circuits using op-amps, connect the circuit ground to supply ground (the black terminal labeled "N" between + and -) — your TA can show you how to do this.* We recognize this circuit as an op-amp integrator in $R_f \to \infty$ limit, so we will call the circuit with $R_f = 100$ kΩ an integrating amplifier.
2. Apply a 500 Hz, 6 V peak-to-peak square wave to the input (with 50% duty cycle). Connect both the input and the output to the oscilloscope, show both signals in the display and sketch the waveforms in the same graph, labeling each signal to identify them. Describe the shape of the output waveform, and explain how it confirms that the circuit acts as an effective integrator. Remember to setup your function generator to High Z mode.

Input : V/div : 1.00V/div t/div : 500µs/div

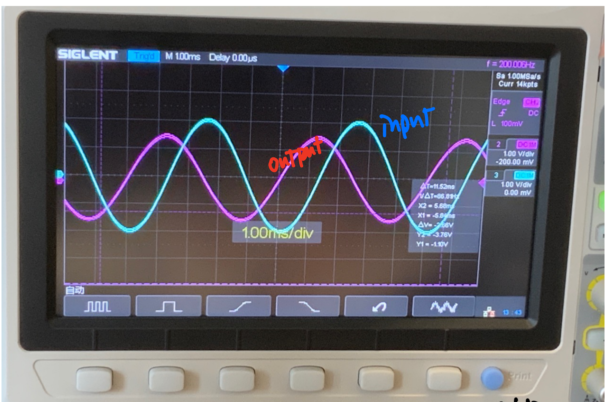
Output : V/div : ______ (____/4)

Describe $v_0(t)$. Does it looks like the integral of $v_i(t)$? Explain: (____/4)

output voltage: oblique line

Yes, the out put voltage is oblique line while the input voltage is square wave.

3. Repeat step 2 for a **co-sinusoid** wave of 200 Hz, 4 V peak-to-peak. LABEL each signal in your graph to identify input and output.



Input : V/div : 1.00V/div t/div : 1.00ms/div

Output : V/div : ______ (____/4)

Describe $v_0(t)$. Does it looks like the integral of $v_i(t)$? Explain: (____/4)

Vo(t) is also co-sinusoid wave

Yes, as integral of co-sinusoid function is still co-sinusoid function.

4. Now change the frequency to 50 Hz and slowly increase the input amplitude from 1 to 6 V peak-to-peak and describe how the output changes as the input increases. (Hint: Is this a linear or non-linear behavior?)

(____/2)

the output amplitude increases as input increases linear

Now increase the input amplitude to 19 V peak-to-peak and describe the shape of the output: (____/2)

the upper peak of the out put amplitude was cut. and remains to be sine-wave

What is the peak-to-peak amplitude of the output waveform when the input amplitude is 19 V peak-to-peak?

$V_{p-p} =$ 28.4 V (____/2)

If you were to increase the amplitude of the input further, would that increase the amplitude of the output substantially? NO (____/1)

How do you explain what is happening to the output?

(____/3)

the intergral ckt reaches saturation, the output is an overdrive voltage for the ckt.
output has value > Vcc

2.3 Non-Inverting Amplifiers

Now you will build the two amplifiers you designed in the prelab and connect them to your envelope detector. (as shown in Figure 8.)

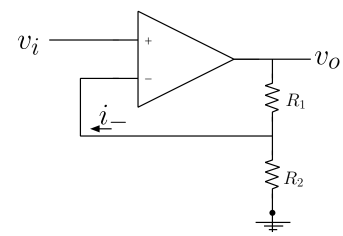


Figure 7: Non-inverting amplifier, showing the signal i_-.

1. First, build the non-inverting amplifier with a gain of 21 that you designed in the prelab. Make sure you connect the DC supplies and the bench ground to your circuit before you apply any voltage to the op-amp inputs. Also, place the circuit near the center of your protoboard, to allow for other circuits to be built on both sides.

2. Apply a 100 Hz sine wave input v_i with 0.5 V peak-to-peak amplitude. Measure v_i and v_o with the oscilloscope. Use "High resolution" and "Quick Measurement". Calculate the voltage gain (you might need to reduce the input if the output saturates):

   $\frac{v_o}{v_i} =$ 21.76 . (____/2)

   How does this compare with the theoretical value? Even if your measurement is very close to the theoretical value, explain what could be the sources of any difference.

   (____/3)

   theoretical value is $(1+\frac{R_1}{R_2})V_i = 21V_i$, so is approximately close to the value.
   the source of diffenence may be resistor is not so aaurate
   and op-amp has current flow into negative node.

3. Disconnect the AC input, and then turn off the DC supplies. Without modifying the non-inverting amplifier you just built, build the non-inverting amplifier with a gain of two that you designed in the prelab. Place your new circuit to the right of your protoboard, allowing for some extra space in between the two amplifiers. Remember that the final circuit will look like Figure 8.

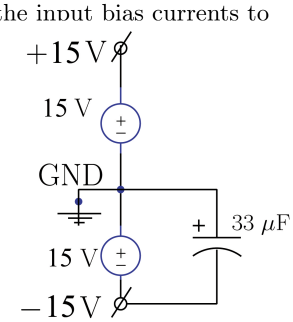
4. Testing the non-inverting amplifier with gain of two: Turn on the DC supplies and connect the AC input (100 Hz sine wave input with 1 V peak-to-peak amplitude) to the new amplifier (gain 2). Observe the voltage gain:

   $\frac{v_o}{v_i} =$ 2.04 . (____/2)

   How does this compare with the theoretical value? very well. (____/2)

5. Remove the AC input. Place your envelope detector circuit (from Lab 1) in between the two amplifier circuits as shown in Figure 8. Note that a 33 μF capacitor is included in the envelope detector circuit to remove DC component from the input signal of the last amplifier (recall that a capacitor acts as an open circuit at DC). A 10 kΩ resistor is connected between the second op-amp input and ground to allow the input bias currents to flow without charging the "decoupling" 33 μF capacitor.

6. Connect the other 33μF electrolytic capacitor in your protoboard, between -15V and ground. This is done to filter out voltage fluctuations produced by the power-supply. Recall that electrolytic capacitors have a voltage polarity requirement. The correct polarity is indicated on the packaging with minus signs and possible arrowheads, denoting the negative terminal. Also the negative terminal lead of radial electrolytic capacitors are shorter. (a reverse-bias voltage above 1 to 1.5 V will destroy the capacitor). Have your TA check your circuit before you continue.



The three-stage circuit that you just built will be part of your radio receiver in Lab 4. As you saw in Lab 1, the envelope detector stage will recover the message from an AM signal. In order for it to work, however, the voltage of input signal must be sufficiently high to turn the diode on and off — hence the first amplifier. The second amplifier, which follows the envelope detector, increases the voltage of the recovered message signal in order to drive a loudspeaker. It also provides a buffer between the envelope detector and the loudspeaker, preventing the loudspeaker from changing the time constant of the tuned envelope detector.

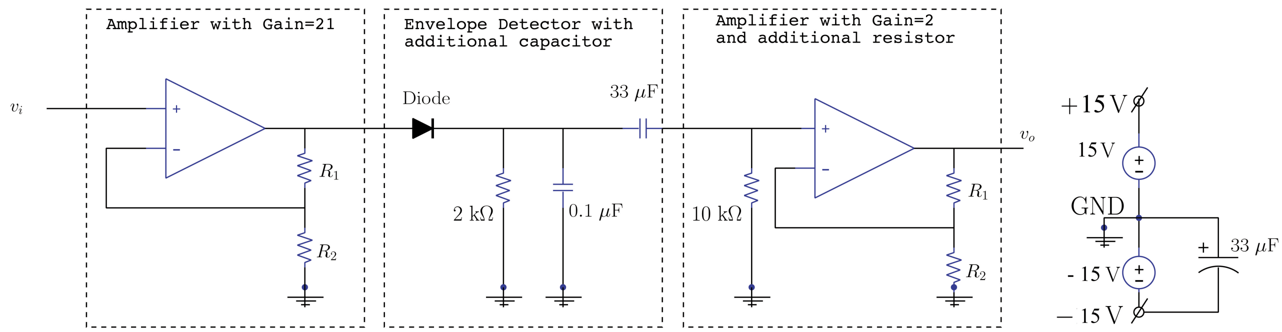


Figure 8: Three-stage circuit for radio.

7. To test your three-stage circuit, create an AM signal with the function generator:
   - Set the function generator to create a 13 kHz sine wave measuring 0.2 V peak-to-peak, no DC offset
   - Press "Shift" then "AM" to enable amplitude modulation
   - Press "Shift" then "Freq" to set the message-signal frequency to 880 Hz
   - Press "Shift" then "Level" to set the modulation depth to 80%. This adjusts the height of the envelope.
   - Listen to the AM signal on the loudspeaker.

   Turn on DC supplies, and connect the function generator to the input of your three-stage circuit. Connect the input and the output of the same circuit to the oscilloscope. Sketch what you see on the oscilloscope display. For sketching the AM signal, you might want to draw a dashed line as the envelope, and filled it. You don't have to draw the carrier signal accurately, but you have to match the amplitude and frequency of the message signal.

Input : V/div : 1.00V/div t/div : 200MS/div
Output : V/div : ________ (____/4)

On the function generator, press "Shift" then "Freq" and describe how the output signal changes while sweeping the message-signal frequency from 100 Hz and 2000 Hz. Be careful not to change the 13 kHz carrier frequency. (____/3)

the wave form of the output voltage be come less sharp upper peaks and become more likely to be sine-wave signals but as the frequency is too high the voltage out put be come less likely to message wave.

8. Until now we have been displaying signals on our oscilloscopes. However, signals in audio frequency range can also be "displayed" acoustically using loudspeakers. **We will next use a corner of our protoboard, an audio jack, and a pair of speakers to *listen* to a number of signal waveforms**: (Note: For this part you don't need your circuit.) Connect the function generator output to the speaker input (via protoboard and audio jack) and generate and listen to a 880 Hz, 1 V peak-to-peak co-sinusoid signal (you need to turn off the AM mode). Repeat for a 13 kHz, 1 V peak-to-peak co-sinusoid signal. Describe what you hear in each case — in what ways 880 Hz and 13 kHz audio signals sound different to your ear?

the 13kHz audio is sharper than 880 Hz audio

(____/2)

9. Set back as input the 0.2 V peak-to-peak AM signal with the carrier frequency of 13 kHz, message frequency of 880 Hz, and modulation depth of 80%. Connect a loudspeaker to the output. Describe what do you hear, and explain what the circuit acomplished.

(____/3)

the volume of the sound would be larger after the ckt.
the ckt acomplish amplification of the signal of the audio

10. Sweep the message signal frequency from 100 Hz to 2000 Hz again. This time describe how the sound changes as the frequency is swept.

(____/3)

the sound become sharper and sharper as frequency is swept.

Important!

Leave your circuit on the protoboard but **return the audio jack to your TA**.

The Next Step

In the next laboratory session, you will continue working with op-amps to build an active filter that will remove noise from your radio signal. You will also use the active filter to study the Fourier series.